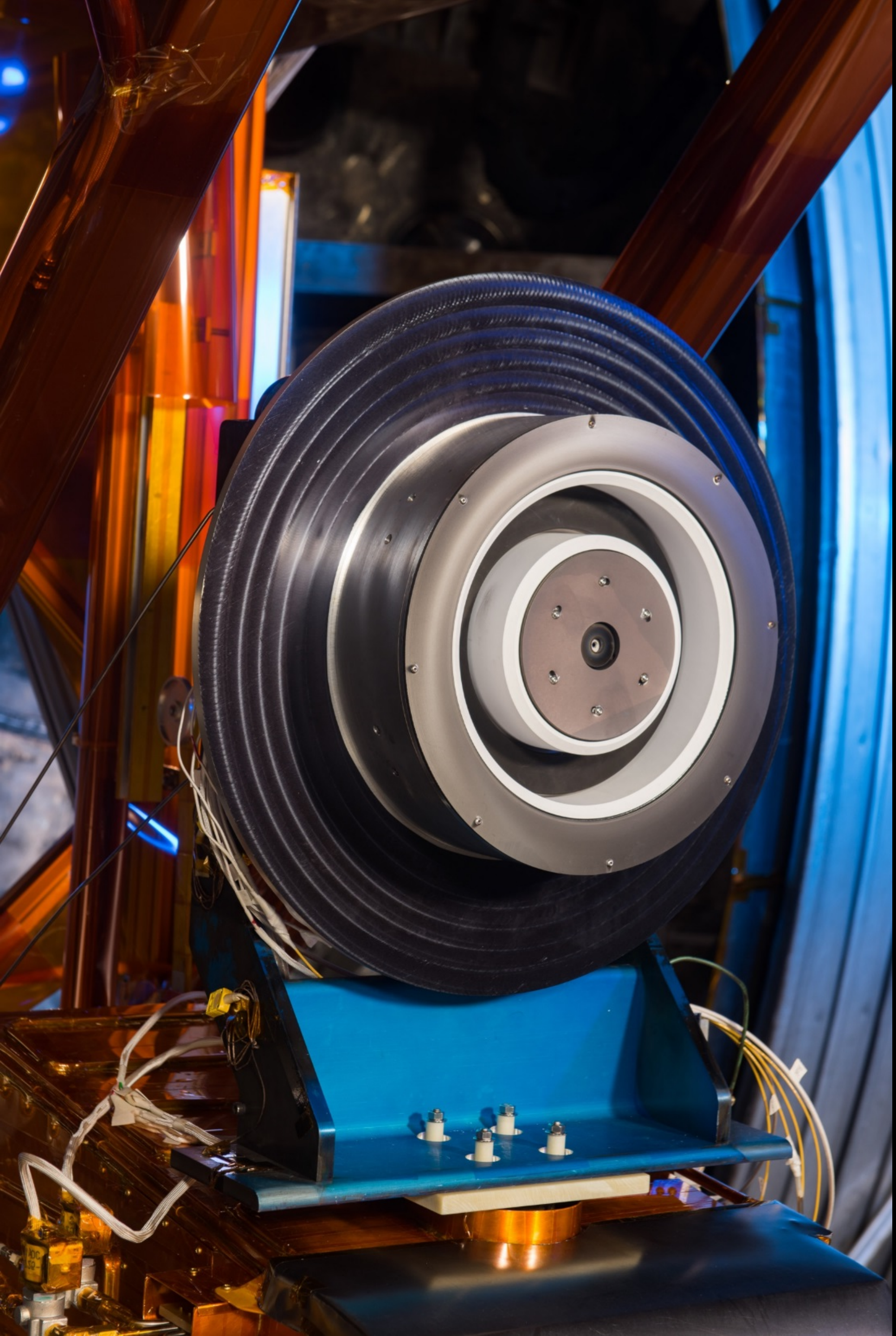


ELECTRIC PROPULSION AND THE GATEWAY:

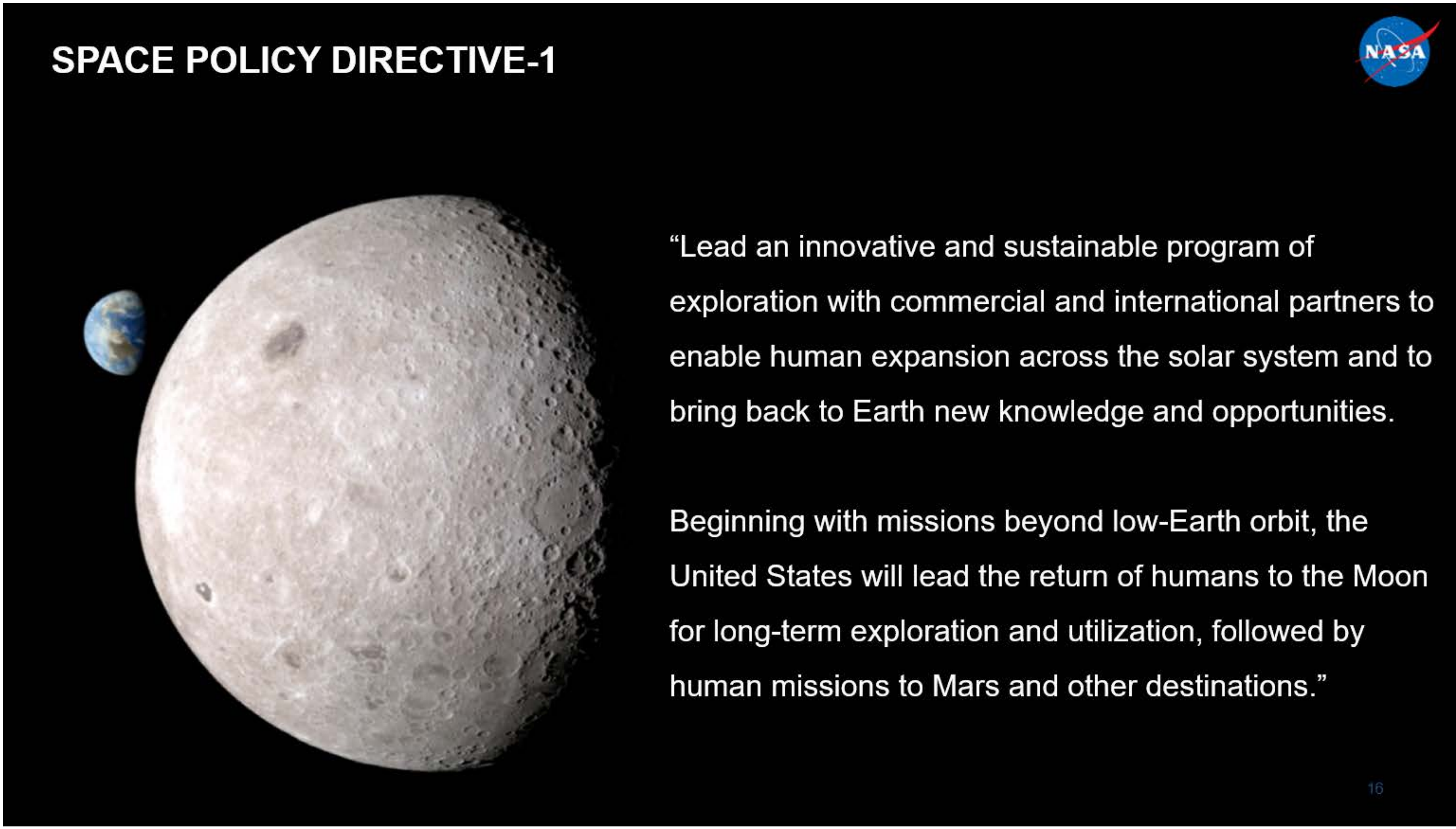
SUSTAINABLE EXPLORATION OF CIS-LUNAR SPACE

Georgia Institute of Technology
Atlanta, GA
April 1, 2019

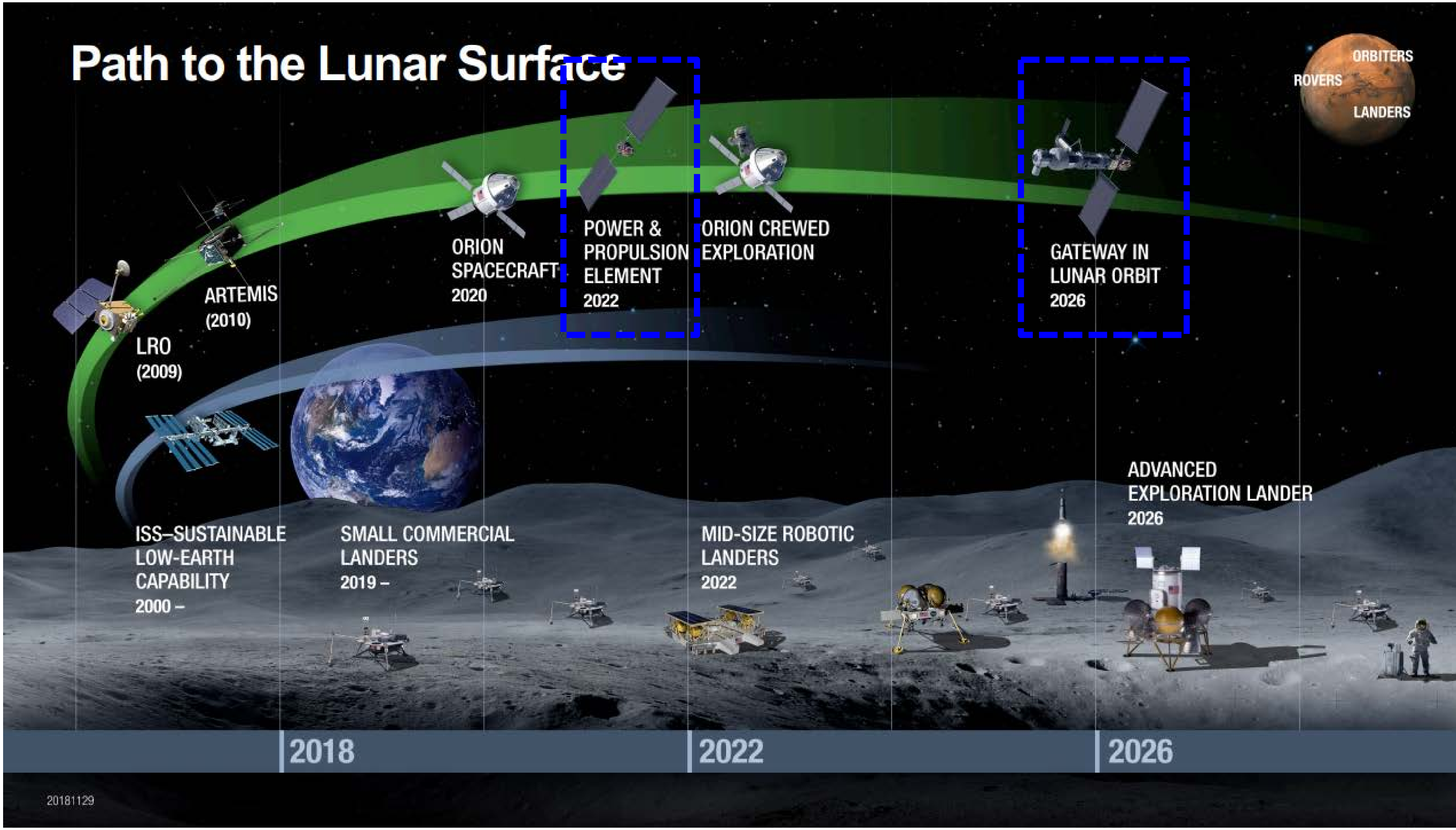
Dr. Jason D. Frieman
Research Engineer
Electric Propulsion Systems Branch
NASA Glenn Research Center

Introduction: Moon to Mars

Space Policy Directive - 1

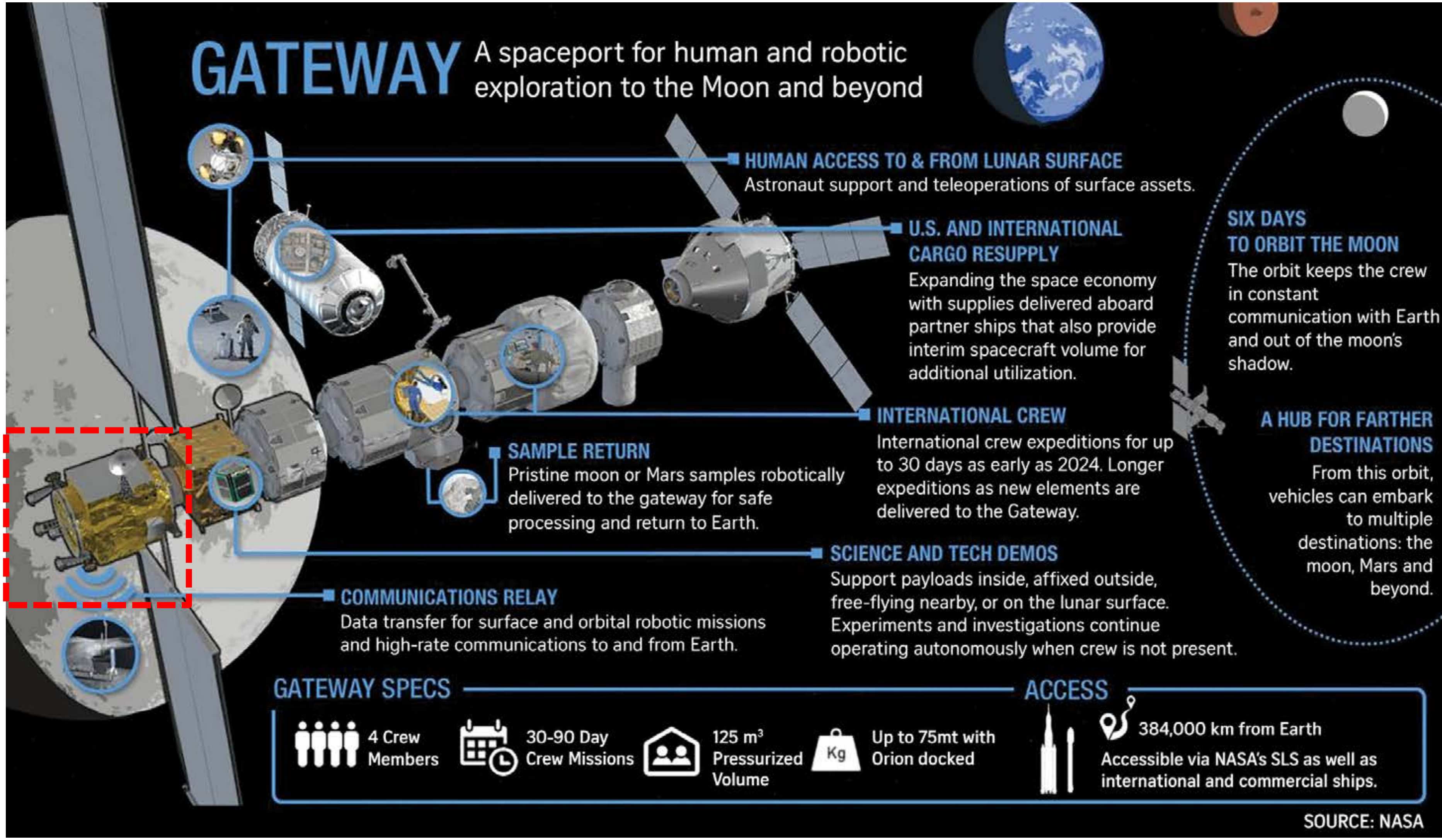


Path to the Lunar Surface

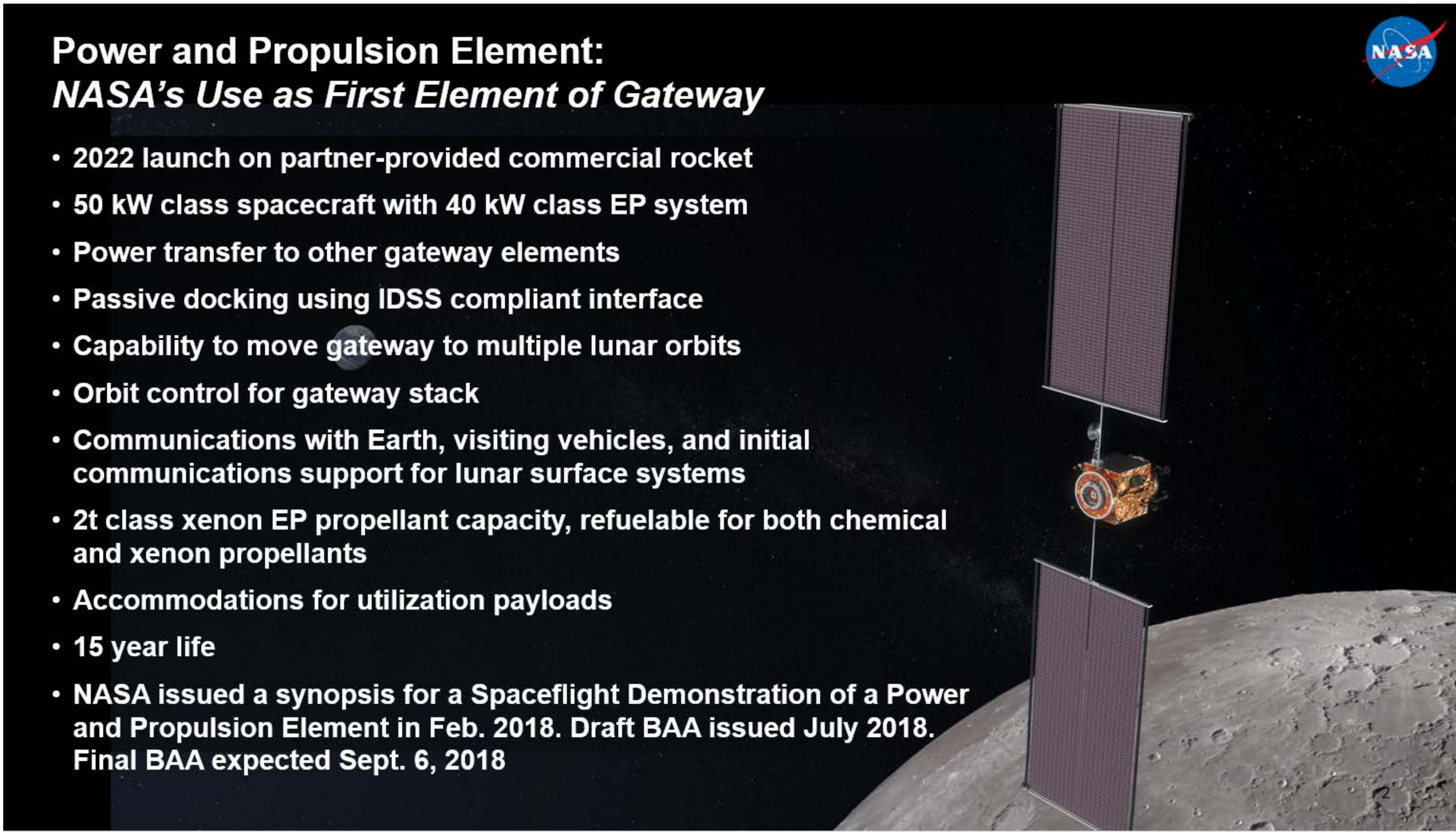


The Gateway: Objectives

The Gateway: Configuration Concept

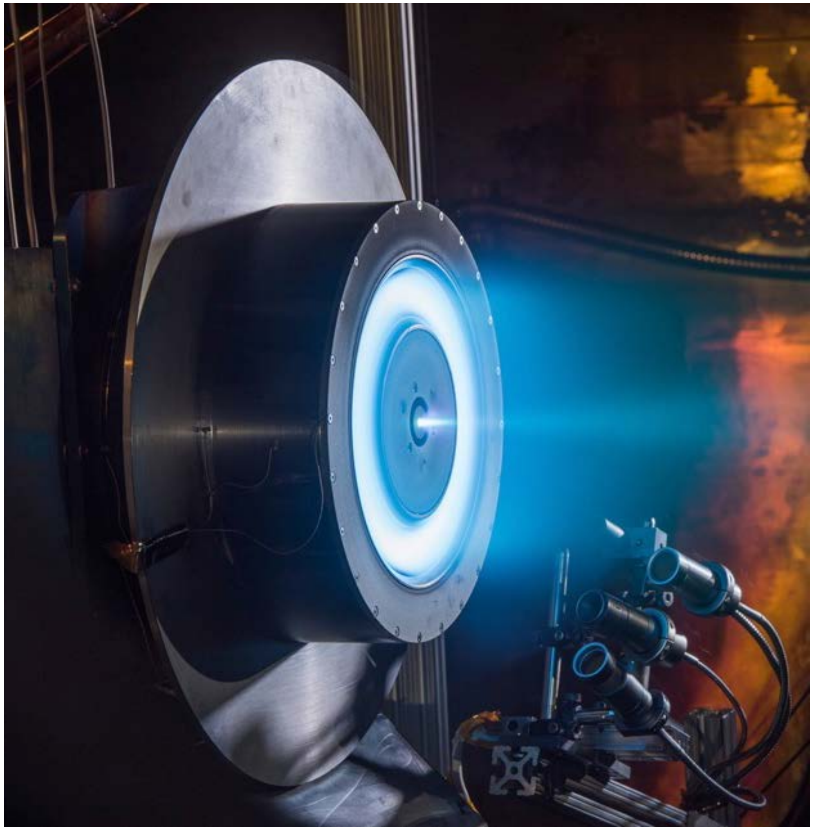


Power and Propulsion Element (PPE)



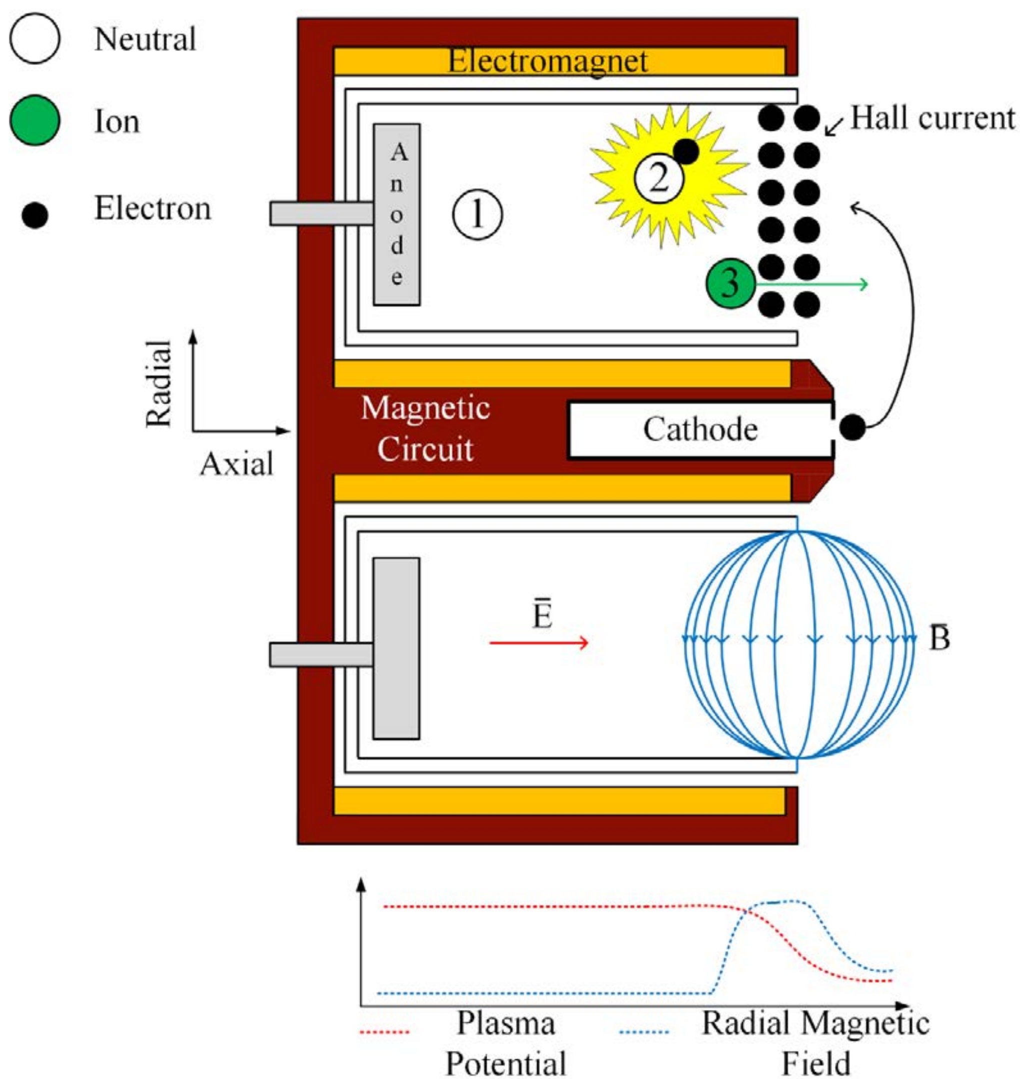
Why Electric Propulsion?

- Fuel (xenon) is storable, does not boil off, and can be resupplied
- Advanced EP provides the ability to move habitat systems to various orbits around the moon
  - Halo, Lagrangian, or other Earth-Moon orbits
- Analyses of in-space orbit transfers in the lunar vicinity shows a 5 to 15 fold savings in propellant with this system as compared to chemical-only systems with equivalent trip times
- Early use supports ensured extensibility to future Mars class transportation system
  - Also directly applicable to a wide range of robotic and human spaceflight missions



Hall Effect Thruster Overview

- Hall effect thrusters (HETs)
  - Electrostatic EP systems that offer:
    - High thrust efficiency
    - High thrust density
  - Theory of operation:
    - Cathode electrons trapped by perpendicular electric and magnetic fields (Hall current)
    - Propellant:
      1. Injected by anode
      2. Collisionally ionized by Hall current
      3. Ion accelerated by electric field to generate thrust



Advanced Electric Propulsion System (AEPS)

- Since 2012, NASA has been developing a 14-kW Hall thruster electric propulsion string that can serve as the building block for the high-power system on PPE
  - Result: Hall Effect Rocket with Magnetic Shielding (HERMeS) Technology Development Units (TDUs)
- Development work transitioned to Aerojet Rocketdyne via a competitive selection for the AEPS contract
  - Contract includes development and qualification of the entire EP string (thruster, power processing unit, xenon flow controller, and harnessing)

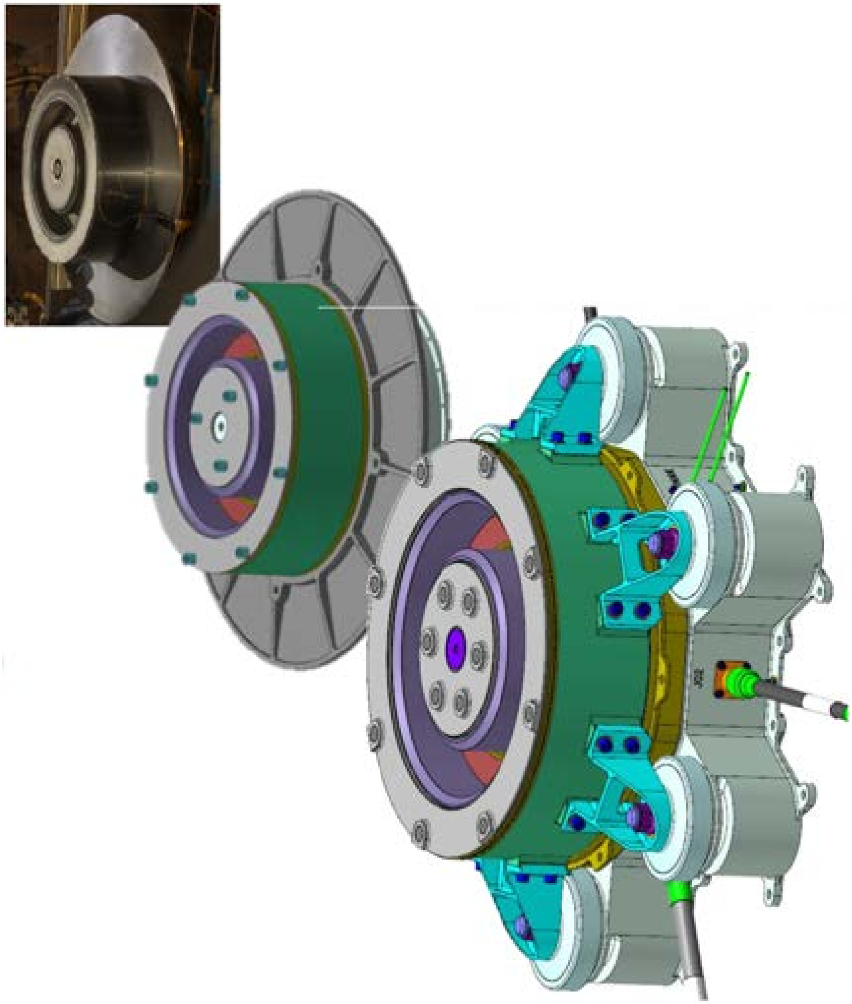
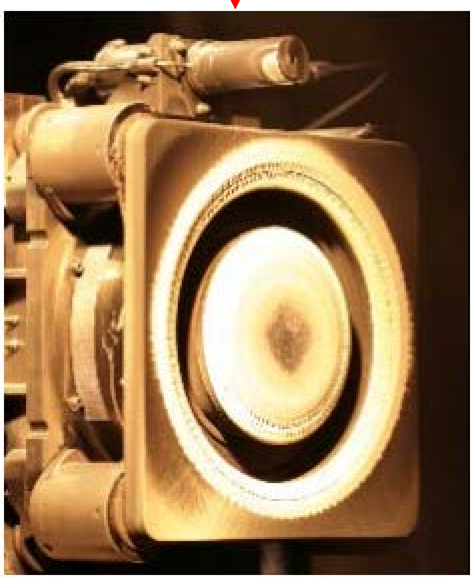


Image from GRC-E-DAA-TN45528

Comparison to State of the Art

Performance Parameter	State of the Art	AEPS
Thruster Input Power	4.5 kW	12.5 kW
Thrust	0.24 N	0.60 N
Specific Impulse	2040 sec	2000-2600 sec
Propellant Throughput	450 kg	1700 kg



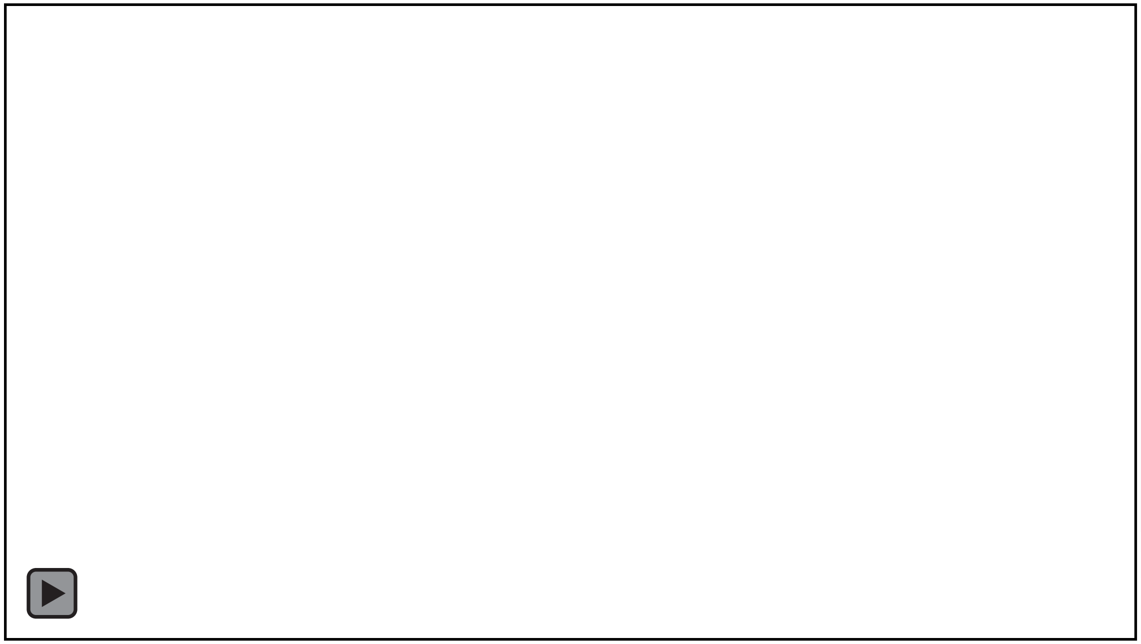
Life limited by erosion of discharge channel

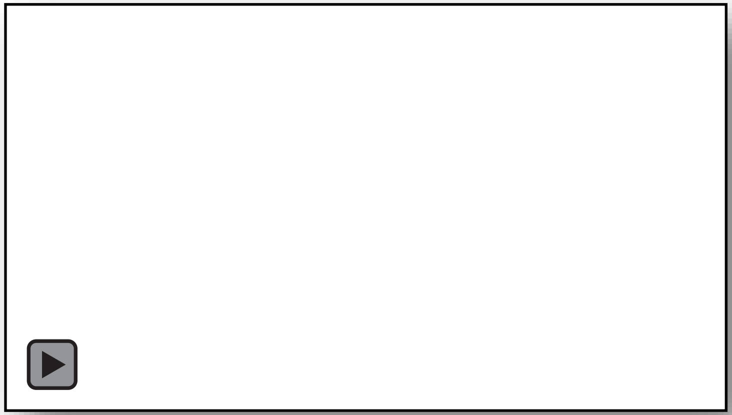
Image from NASA/TM 2006-214453

Magnetic shielding eliminates channel erosion

Life limited by erosion of inner/outer pole covers and keeper (lower rate)

Technology Development Activities at NASA





- NASA continues to support the AEPS development by leveraging in-house expertise, plasma modeling capability, and world-class test facilities
- NASA also executes AEPS and mission risk-reduction activities to support the AEPS development and mission applications
  - Activities include the performance of wear tests to inform service-life assessments for magnetically-shielded thrusters

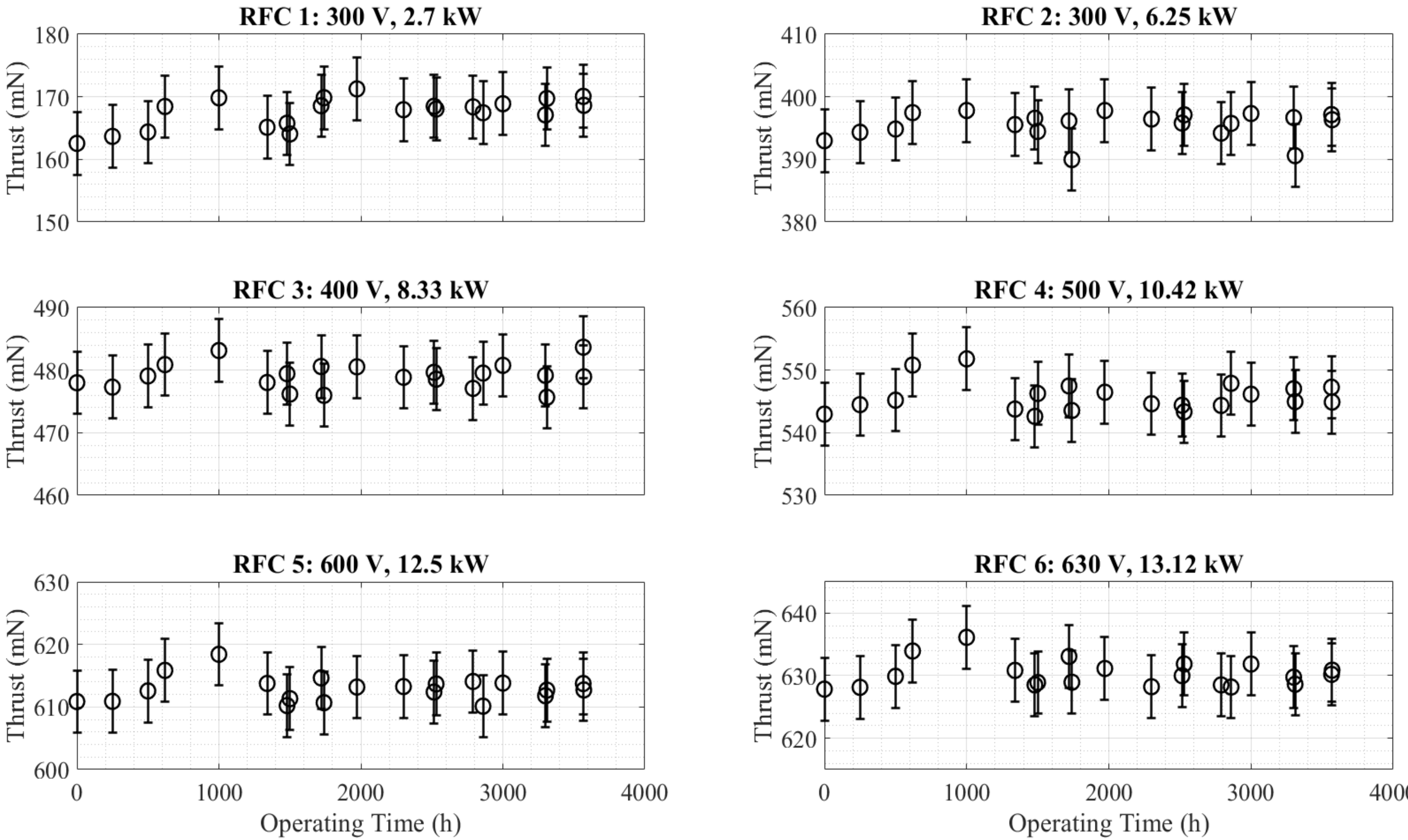
HERMeS Wear Tests

- 2016: TDU-1 Wear Test: AIAA 2016-5025
  - Goal: provide first quantitative insight into wear and performance trends over an extended period of thruster operation
  - 1700 h of operation at 600 V, 12.5 kW

- 2017: TDU-3 Short Duration Wear Test (SDWT): IEPC 2017-207
  - Goal: quantify the impact of operating condition on thruster life
  - 200 h segments (7x) each performed at a different operating condition

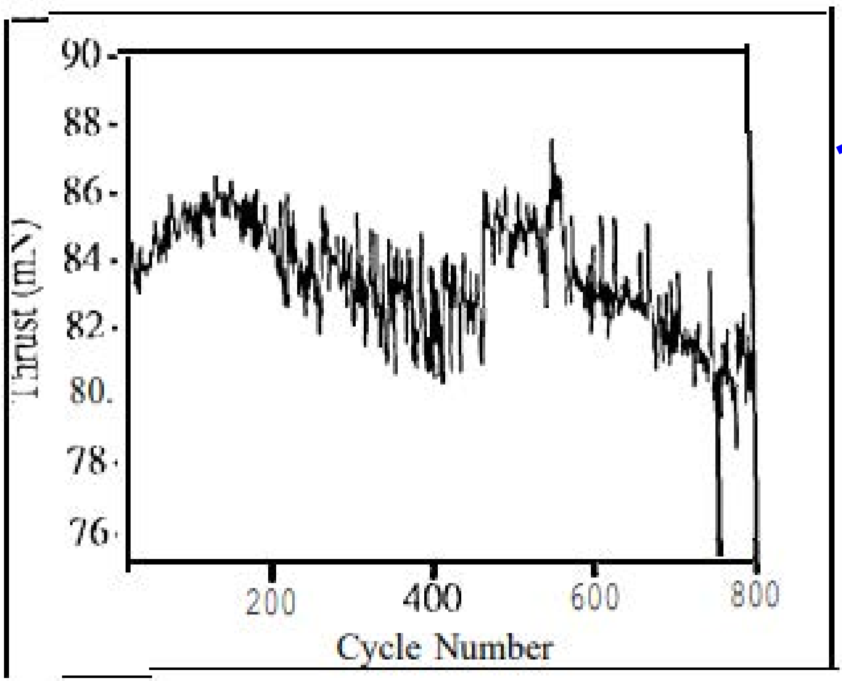
- 2017-2018: TDU-3 Long-Duration Wear Test (LDWT): AIAA 2018-4645
  - Goal: pathfinder test for the planned 23 kh AEPS life and qualification campaign
  - 3,570 h total operation split between 6 segments
    - 2 segments at 600 V, 12.5 kW
    - 3 segments at 300 V, 6.25 kW (impact of magnetic field on wear)
    - 1 segment at 3x nominal facility pressure (impact of background pressure on wear)

Key Findings: Performance



Performance and stability vary by less than the uncertainty during LDWT and when compared against previous TDU wear tests

SOA Hall Thruster



Images from NASA/TM:
20060039356
2006-214453

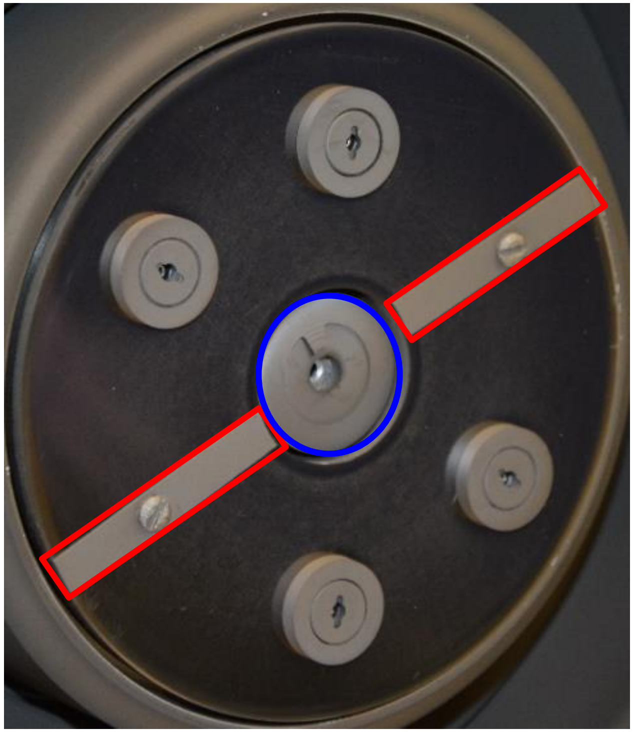
Thrust decrease of ~3% over first 500 h of operation caused by erosion of discharge channel

Constant performance of HERMeS over LDWT indicates effectiveness of magnetic shielding topology

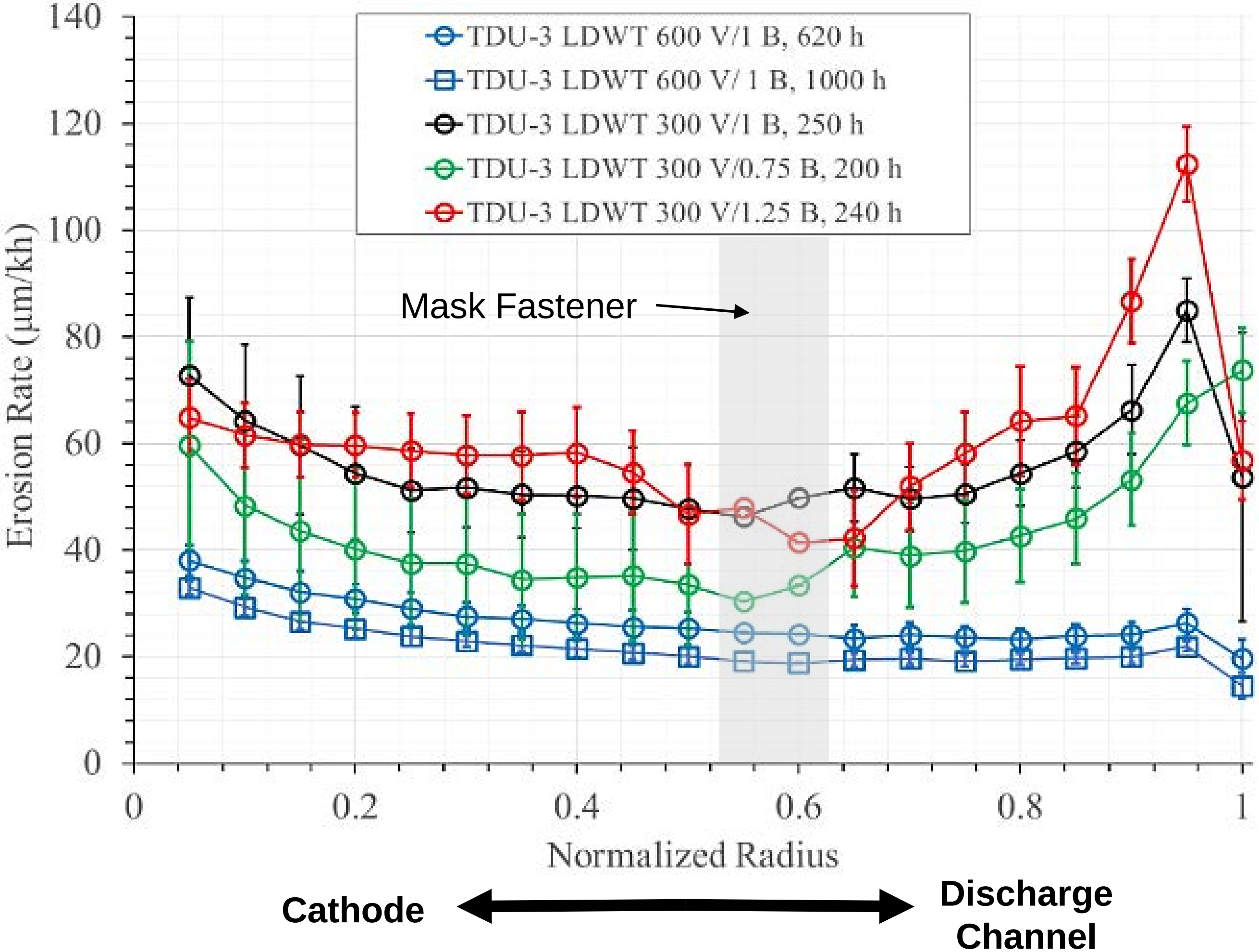
Experimental Apparatus: Wear Measurements

- Graphite IFPC, keeper, and OFPC modified to enable wear measurements
  - Components polished pre-test to maximize surface uniformity
  - Graphite masks installed to provide unexposed reference surfaces:
    - IFPC: two graphite strips covering approximately 95% of radius at 2 and 8 o'clock
    - Keeper: graphite ring with a tab protruding radially inward
    - OFPC: series of graphite strips covering approximately 95% of radius

- Erosion measurements made with a chromatic, white-light, non-contact profilometer
  - Data analyzed per ISO 5436-1 guidance for a type A1 step
  - Typical uncertainties ±2 µm accounting for:
    - Instrument error
    - Surface roughness
    - Non-flat surface geometry



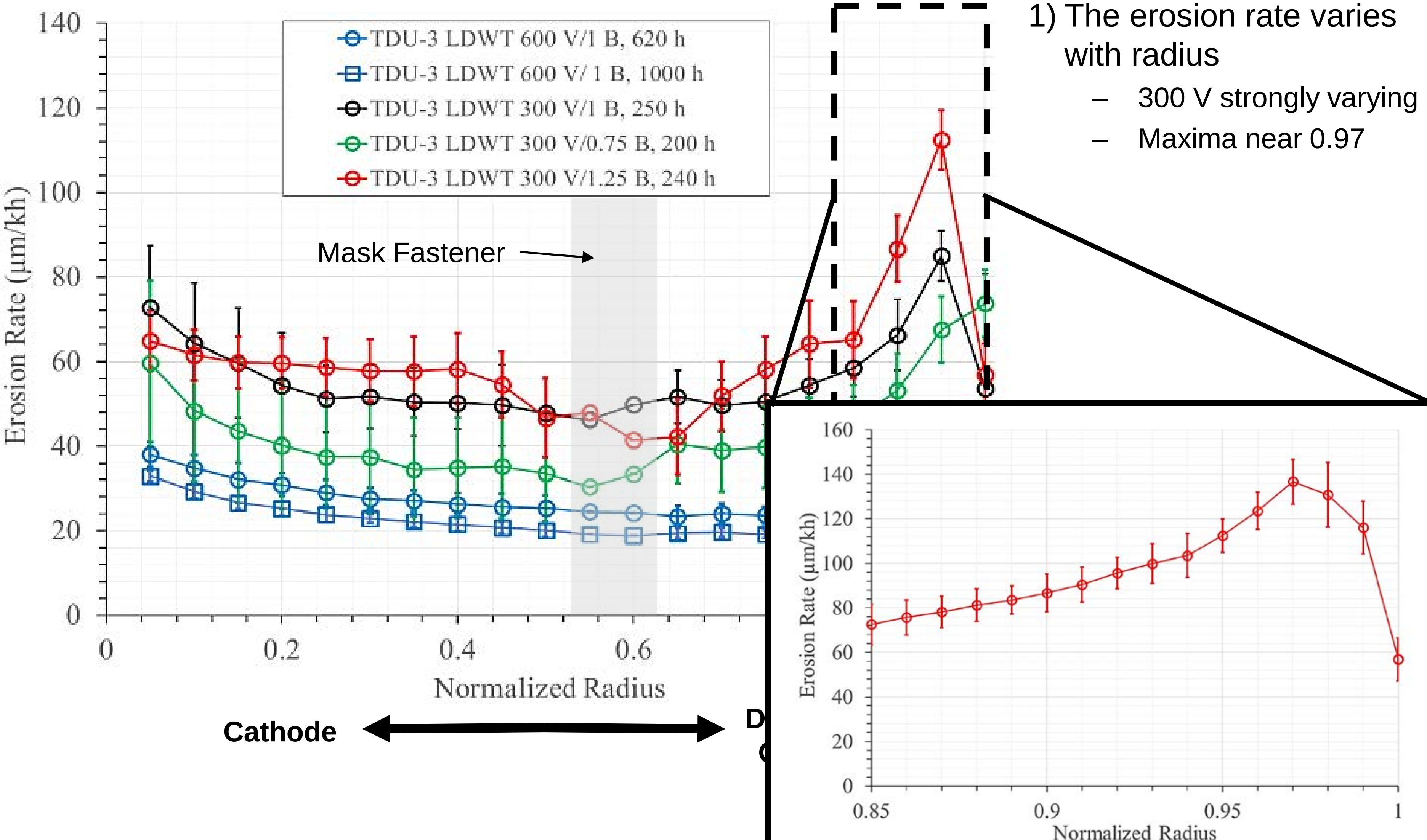
Results: IFPC Wear



Key Observations:

1) The erosion rate varies with radius
   - 300 V strongly varying

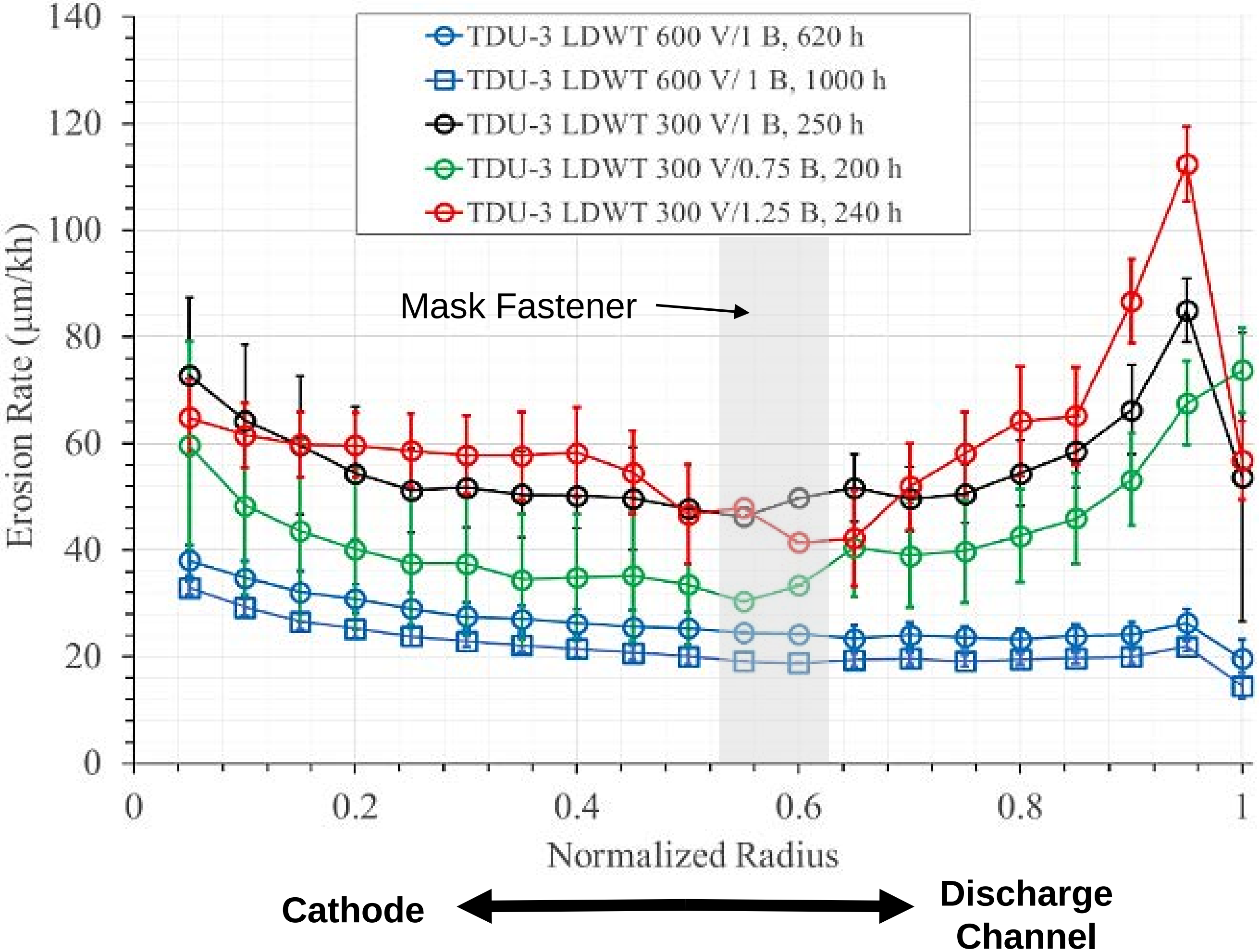
Results: IFPC Wear



Key Observations:

1) The erosion rate varies with radius
   - 300 V strongly varying
   - Maxima near 0.97

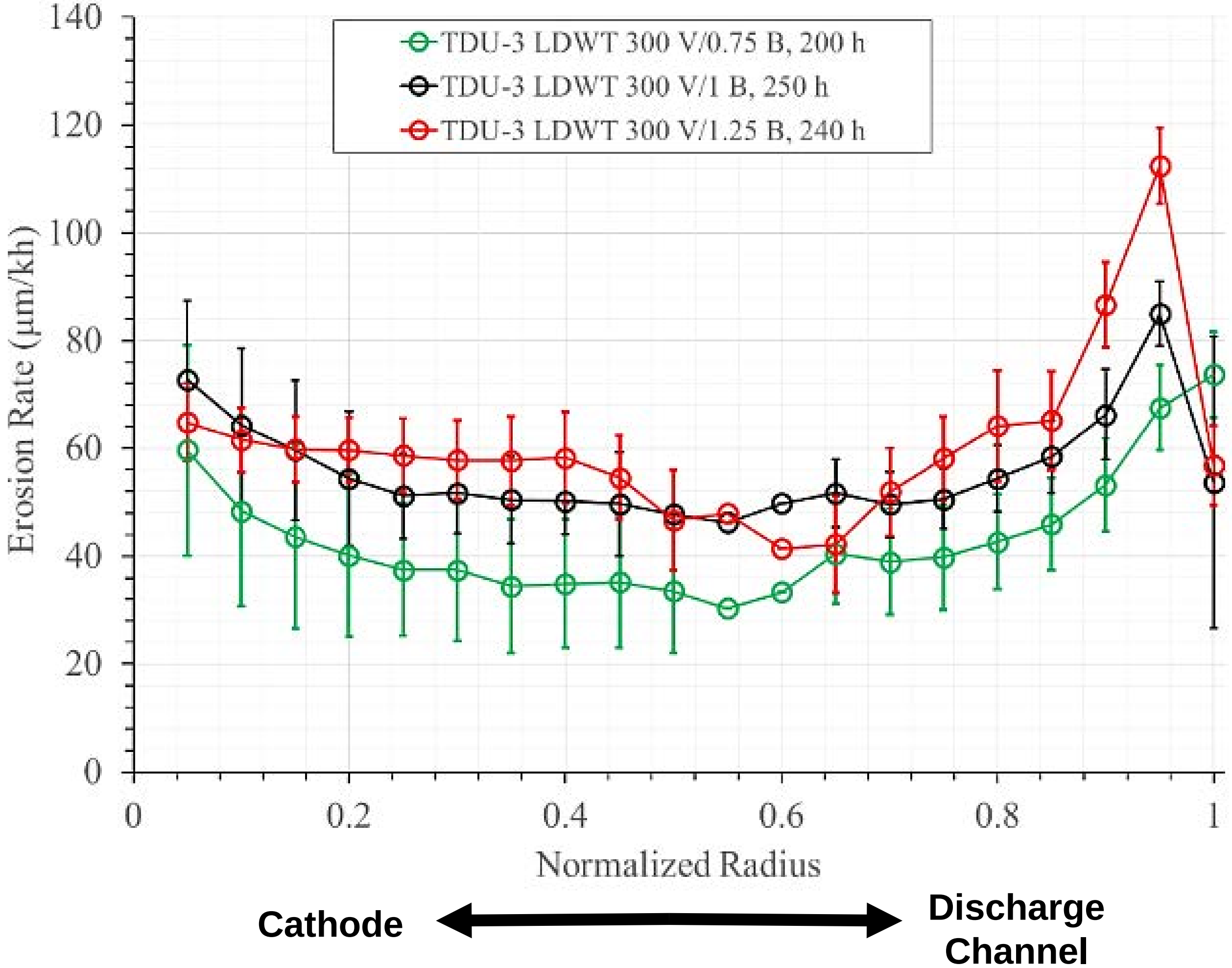
Results: IFPC Wear



Key Observations:

1) The erosion rate varies with radius
   - 300 V strongly varying
   - Maxima near 0.97
2) The erosion rate at 600 V decreases with time
   - Consistent with TDU-1 wear test
3) The erosion rate at 600 V/1 B is 76% less than 300 V/1 B
   - Driven by axial shift in acceleration zone

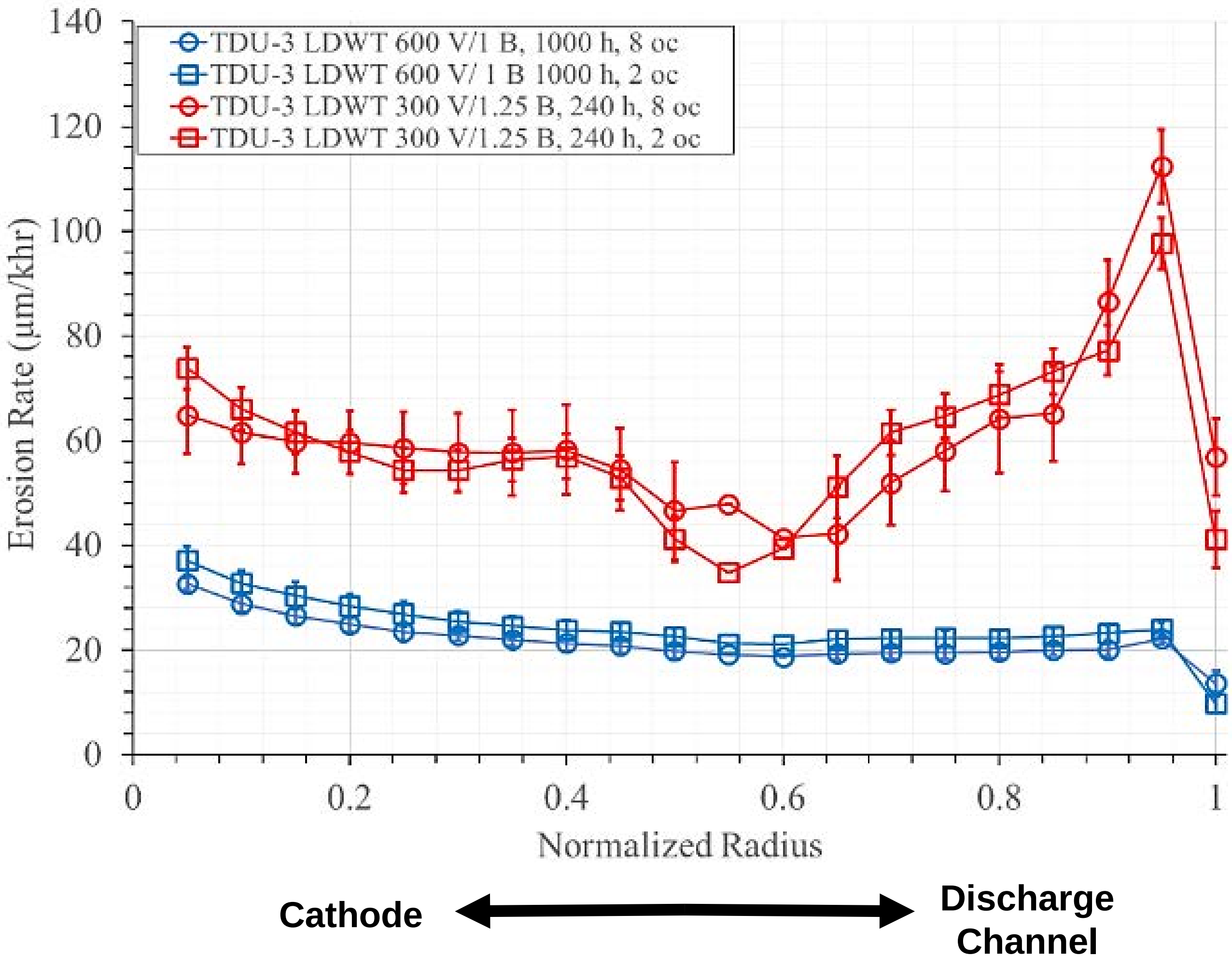
Results: IFPC Wear



Key Observations:

1) The erosion rate varies with radius
   - 300 V strongly varying
   - Maxima near 0.97
2) The erosion rate at 600 V decreases with time
   - Consistent with TDU-1 wear test
3) The erosion rate at 600 V/1 B is 76% less than 300 V/1 B
   - Driven by axial shift in acceleration zone
4) At 300 V, the erosion rate increases with magnetic field strength
   - Cause not presently known

Results: IFPC Wear

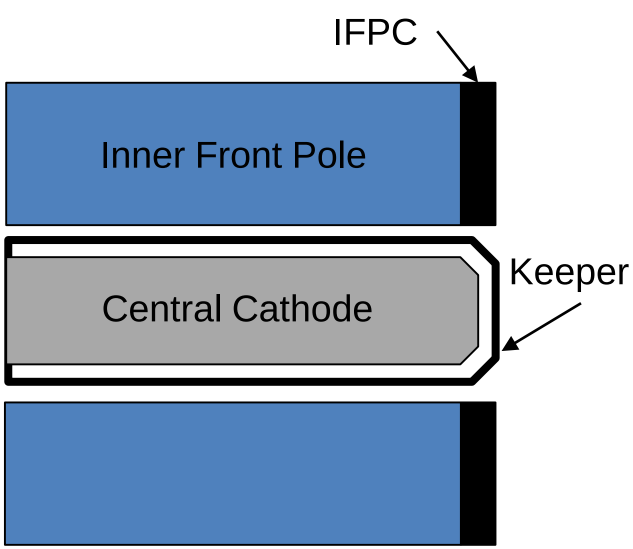


Key Observations:

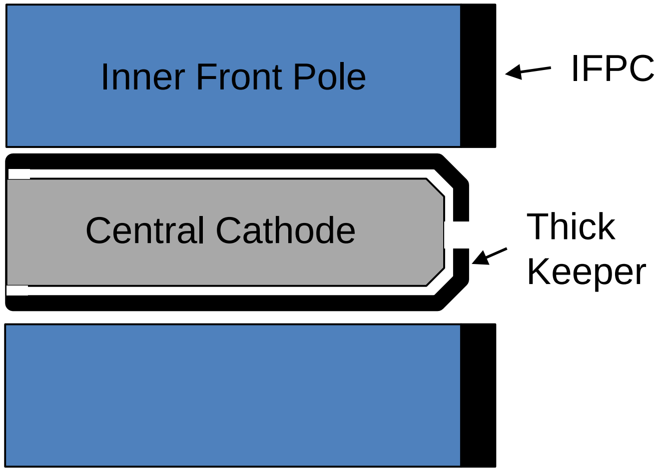
1) The erosion rate varies with radius
   - 300 V strongly varying
   - Maxima near 0.97
2) The erosion rate at 600 V decreases with time
   - Consistent with TDU-1 wear test
3) The erosion rate at 600 V/1 B is 76% less than 300 V/1 B
   - Driven by axial shift in acceleration zone
4) At 300 V, the erosion rate increases with magnetic field strength
   - Cause not presently known
5) IFPC wear is azimuthally symmetric

Results: Keeper Wear

- Keeper position and thickness changed relative to SDWT to try to mitigate elevated wear rates



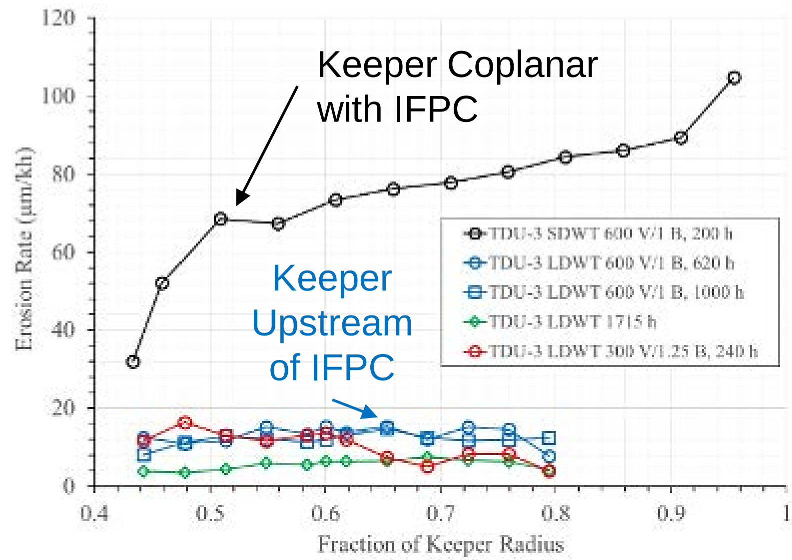
SDWT: Keeper Coplanar with IFPC



LDWT: Keeper Upstream of IFPC

Results: Keeper Wear

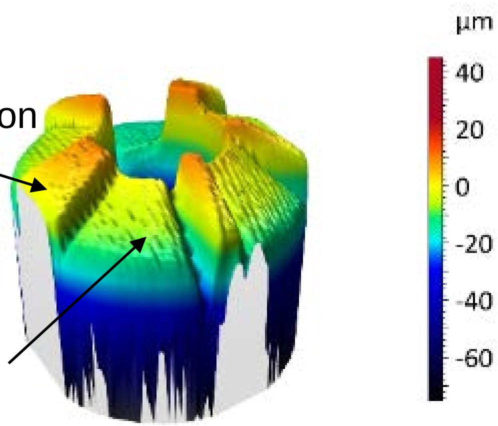
- Keeper position and thickness changed relative to SDWT to try to mitigate elevated wear rates
- Radially-averaged keeper erosion rates for operation at 600 V, 12.5 kW, nominal magnetic field:
  - SDWT: 80 µm/kh (Coplanar Keeper)
    - Rates increase near IFPC and decrease near orifice
  - LDWT: 13 µm/kh (Upstream Keeper)
    - No significant radial variation in erosion rates observed
- Trends qualitatively supported by 3D keeper surface maps



Orifice ⟷ **IFPC**

Masked Region

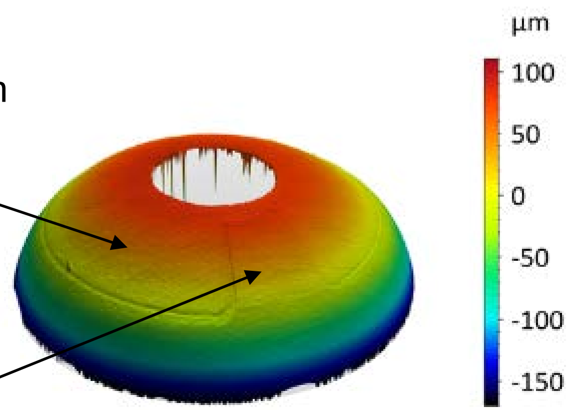
Eroded Region
(~200 h)



SDWT: Keeper Coplanar with IFPC

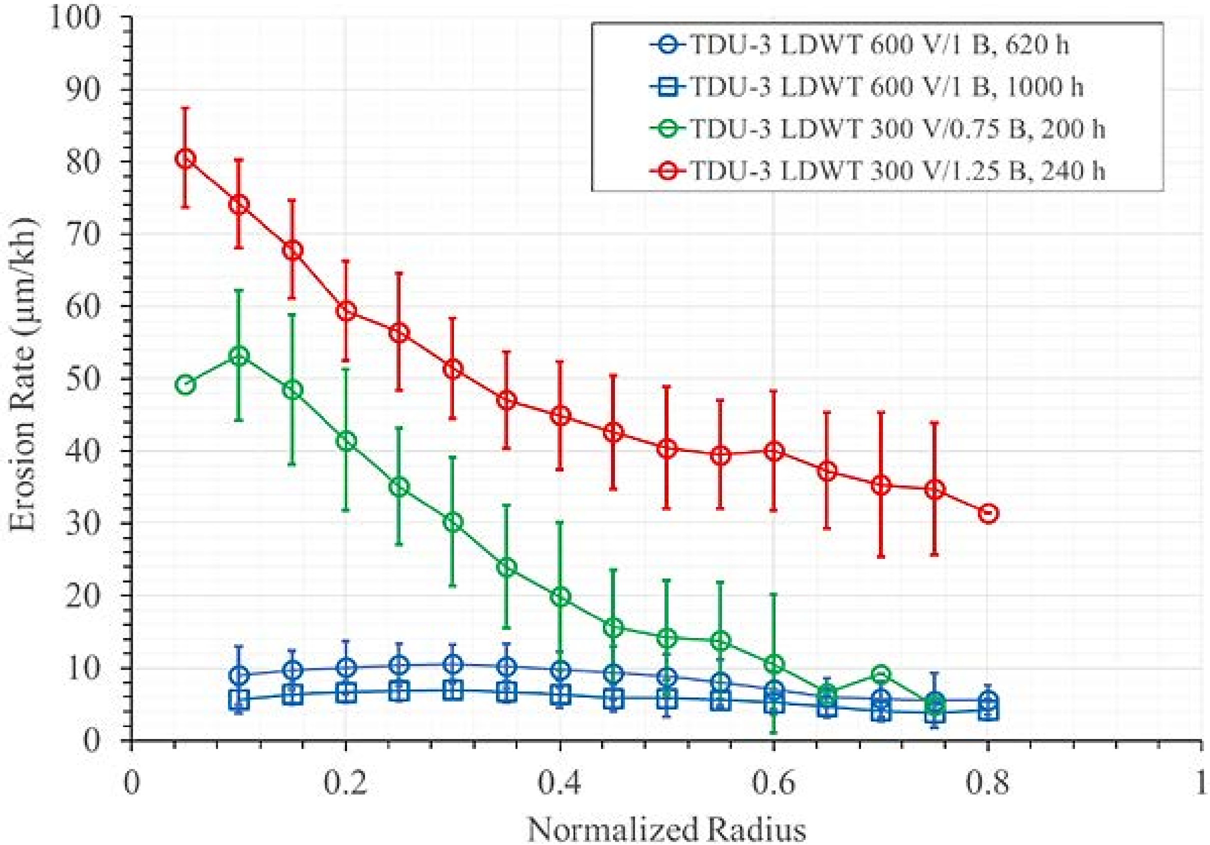
Eroded Region
(1015 h)

Masked Region



LDWT: Keeper Upstream of IFPC

Results: OFPC Wear

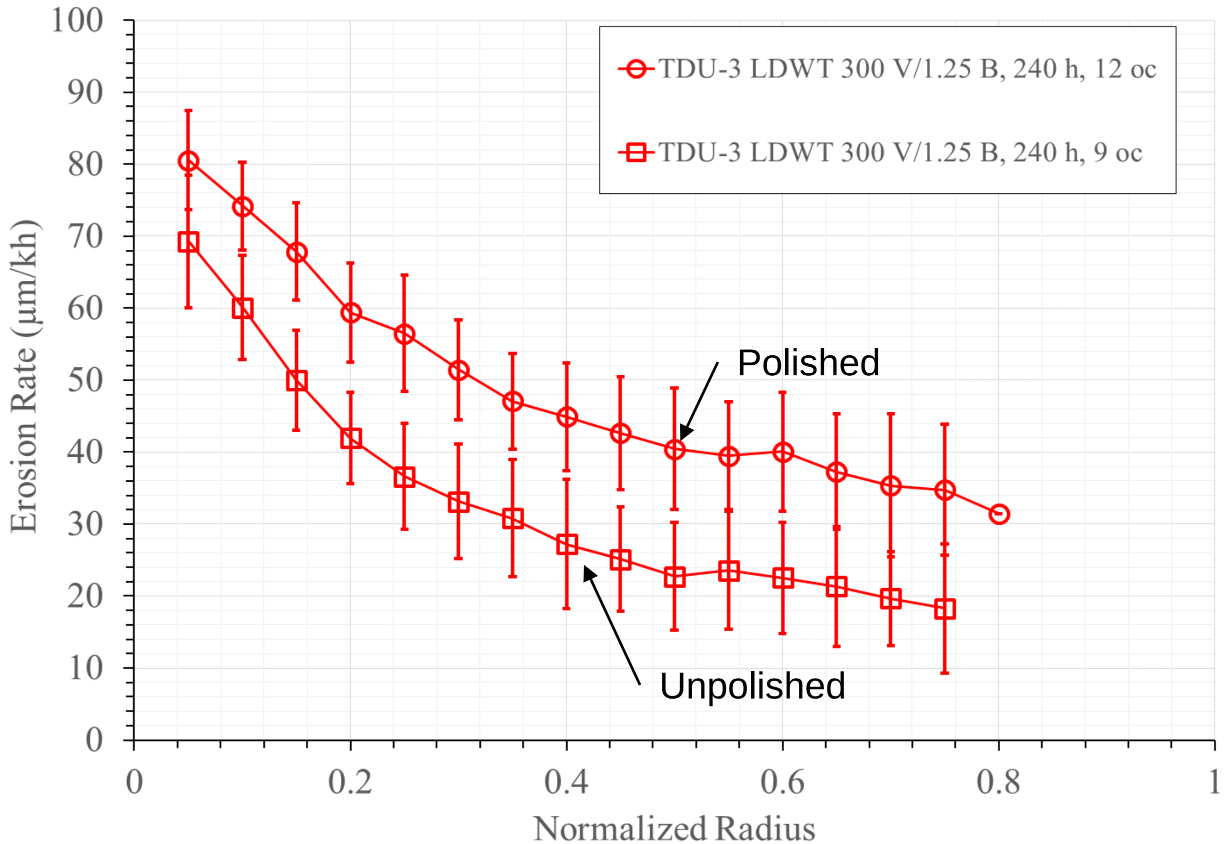


Discharge Channel ⟷ **Outer Thruster Edge**

Key Observations:

1) The erosion rate varies with radius
   - Maxima near channel
2) The erosion rate at 600 V/1 B is 25% of 300 V/0.75 B
3) At 300 V, the erosion rate at 1.25 B is 1.4x higher than at 0.75 B

Results: OFPC Wear



Discharge Channel ⟷ **Outer Thruster Edge**

Key Observations:

1) The erosion rate varies with radius
   - Maxima near channel
2) The erosion rate at 600 V/1 B is 25% of 300 V/0.75 B
3) At 300 V, the erosion rate at 1.25 B is 1.4x higher than at 0.75 B
4) OFPC wear appears azimuthally asymmetric
   - Pre-test surface finish different
   - Suggests possible link between surface finish and erosion rates

Results: OFPC Wear

Beginning of Test: Surface Polished
Higher Erosion Rates

End of Test: Surface Roughened
Lower Erosion Rates

Key Observations:

1) The erosion rate varies with radius
   - Maxima near channel
2) The erosion rate at 600 V/1 B is 25% of 300 V/0.75 B
3) At 300 V, the erosion rate at 1.25 B is 1.4x higher than at 0.75 B
4) OFPC wear appears azimuthally asymmetric
   - Pre-test surface finish different
   - Suggests possible link between surface finish and erosion rates
   - Link would also explain apparent time dependence of IFPC erosion rate

Conclusions

- NASA is committed to a sustainable return of humans to the Moon for long-term exploration and utilization
  - Gateway will enable this sustained cis-lunar presence and provide the capabilities necessary to develop and deploy critical infrastructure
  - The first element of the Gateway is planned to be the Power and Propulsion Element (PPE), which will launch in 2022 with a high-power solar electric propulsion system

- NASA is developing the requisite electric propulsion technologies under the Advanced Electric Propulsion Systems contract with Aerojet Rocketdyne
  - Risk-reduction activities including the performance of wear tests on TDU-level hardware have been completed
  - Engineering hardware fabrication is ongoing and development testing planned to start in 2019

Questions?